Report No.

FOUR-BAND DIFFERENTIAL RADIOMETER FOR MONITORING LNG VAPORS

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(JPL Publication 81-56)

JUNE 26, 1981

FINAL REPORT

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Prepared for

U.S. DEPARTMENT OF TRANSPORTATION

U.S. Coast Guard
Office of Research and Development
Washington, D.C. 20593

(NASA-CR-164637) FOUR BAND DIFFERENTIAL RADIOMETER FOR MONITORING LNG VAPORS Final Report, Dec. 1978 - Jun. 1981 (Jet Propulsion Lab.) 35 p HC A03/MF A01 CSCL 14B G3/35

N81-28418

Unclas 27047

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle	5. Report Date
Final Report - Four Band Differential Radiometer for Monitoring LNG Vapors	June 26, 1981
	6. Performing Organization Code
7. Author(s) J. J. Simmonds	8. Performing Organization Report No. JPL Publication 81-56
9. Performing Organization Name and Address Jet Propulsion Laboratory 4800 Oak Grove Drive Pasadena, CA 91109	10. Work Unit No. (TRAIS) 11. Contract or Grant No. MIPR-Z-70099-8-822868A
12. Sponsoring Agency Name and Address U.S. Coast Guard Office of Research and Development 2100 2nd Street South West Washington, D.C. 20593	13. Type of Report and Period Covered Final Report Dec 78 - Jun 81 14. Sponsoring Agency Code G-DMT-1

15. Supplementary Notes

16. Abstract

During 1978 the Jet Propulsion Laboratory (JPL) developed a Two Band Differential Radiometer (TBDR) to monitor methane concentration during Liquified Natural Gas (LNG) spill tests. The TBDR was successfully tested and used during a series of 5 cubic meter LNG spill tests during the fall of 1978. As a result of these tests, the advantage of being able to monitor the concencration of two other major constituents of LNG, Ethane and Propane was realized.

This report describes the development by JPL of a Four Band Differential Radiometer (FBDR) which is capable of providing a fast rate of response, accurate measurements of Methane, Ethane, and Propane concentrations on the periphery of a dispersing LNG cloud. The FBDR is a small, low power, lightweight, portable instrument system that uses differential absorption of near infrared radiation by the LNG cloud as a technique for the determination of concentration of the three gases as the LNG cloud passes the instrument position.

Instrument design and data analysis approaches are described. The data obtained from the FBDR prototype instrument system deployed in an instrument array during two 40 cubic meter spill tests conducted during the summer of 1980 at the Naval Weapons Center, China Lake, California, are discussed.

17. Key Words	18. Distribution Statement
LNG, FBDR, Methane, Ethane, Propane	This document is available to the U.S. public through the National Technical Information Service Springfield, VA 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified		

Form DOT F 1700.7 (8-72)

ACKNOWLEDGEMENTS

The following individuals at the Jet Propulsion Laboratory contributed to the development of the FBDR Instrument System:

R. A. Britten, J. M. Conley, H. T. Enmark, R. E. Irigoyen, J. C. Mahoney, M. J. McKelvey, D. D. Norris, M. P. Sinha, J. B. Wellman, F. H. Wright, T. C. Young.

We wish to express our appreciation to the personnel of the Lawrence Livermore Laboratory and the Naval Weapons Center who provided support during field testing of the FBDR prototype during the LNG spill tests.

Support for this task by the United States Coast Guard, the Department of Energy, the Gas Research Institute and the National Aeronautics and Space Administration is gratefully acknowledged.

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INTRODUCTION

During 1978 the Jet Propulsion Laboratory (JPL) developed a Two Band Differential Radiometer (TBDR) to monitor Methane concentration during Liquified Natural Gas (LNG) spill tests. The TBDR measured infrared absorption by a dispersing LNG cloud in two spectral bands in the near infrared, one centered on an absorption band for methane and the other at a wavelength band where the LNG constituents do not absorb. The TBDR was successfully tested in the fall of 1978 during a series of five cubic meter spill tests conducted at the Naval Weapons Center (NWC), China Lake, California.[1]

The enrichment of ethane and propane concentration in the LNG as it is spilled (due to differential boil-off rates of the components) was shown during the five cubic meter tests.[2] Also, LNG becomes significantly more explosive as enrichment in the heavier hydrocarbons proceeds.[3] In an effort to characterize the nature of this differential boil-off phenomenon and to provide better modeling data for LNG dispersion, it became evident that instrumentation capable of giving concentration data for ethane and propane in addition to methane would be desirable for inclusion into the instrumentation array for larger scale (40 cubic meter) LNG dispersion tests to be conducted by the Lawrence Livermore Laboratory for the U.S.Department of Energy.[3]

A Four Band Differential Radiometer (FBDR) has been developed by JPL to provide fast, accurate measurements of methane, ethane and propane concentrations on the periphery of an LNG cloud as it disperses from a release on water during LNG spill tests. A prototype and eight field instrument systems have been built and will be used to provide modeling data describing the concentration profiles of the clouds. This data will then be extrapolated to much larger spill volumes in order to assess the safety hazards associated with spills resulting from, for example, large tanker spills offshore.

The FBDR measures absorption of near-infrared radiation at four wavelengths by LNG vapors passing across the instrument absorption region to provide point source monitoring of methane, ethane and propane concentrations with accuracies of 0.2% or 10% of measurement, whichever is greater. It is a small, easily portable, lightweight, low-power instrument system which interfaces to a field data acquisition system designed by the Lawrence Livermore Laboratory.[4] Raw instrument data is transmitted via radio link by the field station to a trailer at a remote site and is reduced to concentration values after completion of the spill test.

The following sections describe the instrument design, function, and data analysis. Results obtained by the prototype FBDR deployed during three 40 cubic meter LNG spill tests conducted in California at NWC, China Lake, during the summer of 1980 are discussed in Appendix 1.

INSTRUMENT DESCRIPTION

Figure 1 is a photograph of the instrument system. The enclosures are sealed to protect the optics and electronics from degradation by dust and moisture, as well as preventing the entrance of any of the measured gases into parts of the optical path where unwanted absorption might occur. The sealed units also prevent exposure of any potential ignition source within the instrument enclosures to the LNG cloud.

The sensor head is 21.5 cm long, 19 cm wide, and 8 cm in height and weighs 2.3 kg. Figure 2 is a view of the interior of the sensor head. Figure 3 shows the optical layout schematically. The source, shown in the upper left, is a small incandescent lamp operated at approximately 2150°K. The radiant energy emitted by the source is chopped at 90 Hz by a four aperture chopper blade. The chopper is driven by a four phase 45° stepper motor operated at 180 pulses per second (1350 RPM). An LED phototransistor pair mounted across the chopper aperture provides a phase reference to the demodulator circuitry. The chopped beam then illuminates the housing mounted lens (L_1) which is the entrance pupil of the optical system. The f/3.2 light bundle then traverses the 15 cm long absorption region four times as defined by the three fold mirrors (M_1, M_2, M_3) giving a total absorption path length of 60 cm. The bundle re-enters the housing through a window which is the aperture stop of the system, and is divided by a beamsplitter (BS_1). The reflected bundle is deviated 90° and the transmitted bundle is folded 90° by the 100% mirror (M_4).

The two parallel bundles are then passed by the relay lenses (L_3 and L_4 respectively) which relay the image of the entrance pupil onto the detectors. Prior to irradiating the detectors, the two bundles are split again by beamsplitters (BS_2 and BS_3) mounted on the detector block. Thus, four discrete 90 Hz modulated polychromatic bundles are formed, each of which passes through a narrow bandpass interference filter prior to irradiating a lead sulfide photoconducting detector masked to 1.8 mm diameter.

Each detector is in series with a load resistor and DC bias voltage. Output is monitored across the detector. The 90 Hz AC signal output of the detectors is amplified in the sensor head and carried down the mast by cables to the Ground Electronics Enclosure. The Ground Enclosure contains the remaining signal chain electronics (bandpass filters, demodulator, integrate and hold, analog multiplexer, and analog-to-digital converter) as well as digital interface circuits, thermal control servo circuits and dc-to-dc converters.

The instrument data interfaces with a large-scale Field Data Acquisition System (FDAS). Each instrument channel output is integrated simultaneously and the resulting signals are multiplexed and converted to a digital frame consisting of 16 eight bit bytes at a 10 Hz rate.

DESIGN CONSIDERATIONS

Operational Design

As the FBDR instrument will be used in a large scale array of field instrumentation around LNG Spill Test facilities, several constraints were placed on the operational characteristics of the system. First, the instrument was to have a low power requirement to allow a gel cell battery charged by a small array of solar cells to provide all the necessary energy required by several instruments mounted on a single field station mast. To this end, power consumption was a major design criterion. A low power IR source was selected. Selection of the chopper motor and associated drive circuitry was driven by the power constraint. The operating temperature of the detectors was selected to be 20°C rather than a lower temperature (which would have given better performance) so the thermal control servo system would need less power to operate. CMOS components were used wherever possible and efficient dc-to-dc converters were specified.

In order to decrease total power drain on the battery during the period of preparation for a spill and during the hold periods while waiting for appropriate weather conditions, the instrument was designed to have separate standby and operating modes. During waiting and preparation periods the instrument operates in a standby mode during which only the thermal control system and necessary dc-to-dc converters operate. Just prior to the spill the instrument is commanded to full operation and is ready to transmit data in approximately 10 to 15 seconds. The system draws approximately 5 watts in standby mode and 25 watts in the fully operational mode.

The system was packaged in two easily portable enclosures. The sensor head, capable of being mounted with several other instruments on a lightweight aluminum mast, contains the electro-optical system and preamplifier electronics.

It is small and lightweight with a small frontal area presented to the spill cloud front. The small frontal area minimizes disturbances to the free flow of the dispersing LNG cloud as it passes the instrument. The Ground Electronics Enclosure is a lightweight, deep drawn aluminum box 22 cm wide, 33 cm long and 23 cm in height which contains the remainder of the system electronics. It is mated to the sensor head by two cables. A photograph of a sensor head and ground electronics enclosure mounted on a field station mast is shown in Figure 4.

Spectral

Methane, ethane and propane have strong absorption bands in the 3.0 - 3.5 and 2.0 - 2.5 μm wavelength regions of the near-infrared with strong differential absorption also evident. It is upon this differential absorption of radiation by the three gases at the four wavelength bands that the design of the FBDR is predicated. The filters employed to define the absorption passband are glass substrate narrow bandpass interference filters centered at 2.02, 2.36, 2.46 and 2.51 μm with bandwidths of approximately 400Å. The methods used to obtain concentration data by making absorption measurements of the LNG cloud at these wavelengths are described in the data analysis section below.

The 2.0 - 2.5 μm region was chosen for use in the FBDR. Although the 3.0 - 3.5 μm region shows stronger absorption by the three gases, there is strong differential absorption in the 2.0 μm region as can be seen from the transmission spectra of the three gases in Figures 5, 6, and 7. Water vapor is transparent in this region when the short path length is considered[5] and performance of the system is not degraded by normally present atmospheric gases (N_2, O_2, Ar, CO_2). The greatest advantage in choosing this spectral region is in the simplified optical system design and implementation made possible. Readily available, low cost crown glass may be used as a substrate for the transmission elements as opposed to expensive, specialized optical materials that would be required to obtain adequate performance in the longer wavelength region. Additionally, a low power incandescent source provides adequate radiance in the wavelength region chosen, whereas work in the longer wavelengths would require a black body-type source drawing considerably more power. Because of this region's proximity to the visible wavelengths, the beamsplitters employed may be specified in the visible at greatly reduced cost without introducing large errors in the estimation of their performance around 2 μm.

Optical

As described above, the choice of the wavelength region employed in the FBDR system allowed the use of less expensive optical substrates as well as relaxed characteristics and specifications for the beamsplitters and the source. These approaches enabled the optical system to be simplifed from that which would have been required had a longer wavelength region been selected.

The optical system described in the Instrument Description above relays the image of a uniformly illuminated entrance pupil onto the four detector planes. The images are uniform discs approximately 2.0 mm in diameter which overfill the 1.8 mm diameter active areas of the detectors. By overfilling each detector with uniform illumination, the susceptibility of the signal to fluctuations due to vibration of the source filament, outboard optics platform, etc., is significantly decreased from that which would occur if the image of the source filament itself had been imaged on the detectors (due to the non-uniformity of response over the the detectors' active areas).

The temperature of exposed optical surfaces is controlled to maintain their temperatures above dew point in order to prevent fogging when the instrument re-enters a warm, humid atmosphere after being enveloped for some time in the cryogenic cloud of LNG.

Type and Number of Detectors

Lead sulfide photoconductive detectors were selected for incorporation into the FBDR design based on their high performance in the wavelength region of interest at room temperature. As described above, operation at the low temperatures which would be required by other types of detectors was not practical due to the power required for cooling. Lead sulfide (PbS) performs well at 20-25°C and 90 Hz modulation frequency with high D* (typically 5×10^{10} cm $Hz^{1/2}W^{-1}$).[6] Responsivity was measured under the instrument operating conditions to be $\cong 4 \times 10^4$ V/W.

Two sampling techniques were considered: one, using a single detector and a filter chopper wheel in which each wavelength is sampled sequentially through a single signal chain; and the second, using four detectors each with individual filtering, a clear aperture chopper and four discrete multiplexed signal chains. The second method was chosen as it does provide truly simultaneous detection at all four wavelengths although thermal control required for the detectors is more stringent as will be described below. A single detector design would have been easier to implement, but not enough is known about the turbulence characteristics of the dispersing LNG cloud. There is a potential for significant error in measurement accuracy due to a complex form of aliasing using sequential sampling if turbulence induced changes in the composition of the gas mixture present in the absorption region occur at frequencies greater than half the sampling frequency. Even with simultaneous detection using four detectors, aliasing is still possible in the concentration contours obtained from many samples; however, the results from individual sample periods will be correct.

Thermal Control

The choice of using four detectors in the FBDR brings about the requirement that the operating temperature of the detectors be controlled in order to stabilize the relative responsivity of the detectors. Individual lead sulfide detectors vary significantly in responsivity with respect to temperature with a typical value of approximately 4%/°C.[6]

In order to meet threshold and accuracy requirements it was determined that the relative sensitivity of the four detectors must remain constant to within 1 part in 5000. This is achieved by controlling the stability of the detectors' temperature to within ±.05°C with a Peltier cooler located beneath the thermally isolated detector block with its hot junction dissipating to the sensor head housing. The temperature control stabilizes relative sensitivity to 1 part in 2500. The additional stability required is gained by selecting each individual set of four detectors for responsivity within 5% of one another. Controlling these two parameters yields the required 1 part in 5000 uniformity of response for each set of detectors.

Signal Chain Electronics

Figure 8 is a block diagram of the instrument system showing the major sub-divisions of the electronics for the FBDR. Up to the analog-to-digital converter, the signal chains for each detector channel are separate. In the sensor head, each detector output is AC coupled to a unity-gain preamplifier and low pass filter which rejects frequencies greater than 3 KHz eliminating the passage of high frequency noise to the gain stages of the signal chain. The low level detector signals (≅ 150 mV peak to peak) are then amplified to 20 volt peak-to-peak levels and carried down cables to the Ground Electronics Enclosure. In the ground enclosure, each signal is received by a differential amplifier, utilized to increase common mode rejection, and is then further conditioned by a bandpass filter with bandwidth of 20 Hz centered on 90 Hz to attenuate low and high frequency noise components. The signals are then synchronously demodulated and input to the integrate and hold circuits. The demodulator obtains its phase reference from the chopper-mounted optical switch. The integrate and hold circuits sample each signal eight times (two full revolutions of the four aperture chopper wheel) to provide a summing integration which desensitizes the system to small differences in detector exposure time due to nonuniformities in the size of the the chopper apertures. The four detector signals as well as three housekeeping channel signals (detector block temperature, case temperature, and system input voltage) are multiplexed and then converted to 12 bit digital format by the analog-to-digital converter which outputs to the interface electronics.

Interface Electronics

The interface electronics receive the seven channels of data from the A/D converter, format them and transmit the information to the FDAS as a serial, asynchronous data stream. The circuits also store and transmit the numerical coefficients required for data reduction. In addition to controlling instrument data output to the acquisition system, the interface circuits provide all necessary control signals and clocks to the demodulators, integrators, multiplexer, A/D and motor control.

Control Circuits

Several control circuits are employed in the FBDR system. The detector thermal control is a closed-loop analog servo which employs both integral and proportional gain loops to drive the Peltier cooler mounted under the detector block.

The control circuit for the optics heaters is an open loop analog circuit which monitors error signals from a case-mounted thermistor to turn surface heaters bonded to the exposed optical elements on and off to maintain the temperature of these elements above the dew point to prevent fogging.

The stepper motor which drives the chopper is controlled to give 90 Hz modulation of the source beam which is stable to within .05 Hz. The circuit utilizes a single chip stepper driver which obtains its frequency reference from the same crystal oscillator that references the integrators, demodulator and A/D converters.

Power and Grounding

The various voltages required for instrument operation are derived from an external 12 volt battery by DC-to-DC converters in the Ground Electronics Enclosure. In addition to providing the necessary voltages, the converters also isolate the FBDR system from possible noise sources injected onto the line by other systems running from the same battery.

All grounds and return lines are brought to a single point in each enclosure (Sensor Head and Ground Enclosure) and these points are tied together at the instrument interface connector to form the instrument ground which is carried to earth by the FDAS. Isolation between the instrument signal ground and the FDAS is provided by the use of optical couplers in the data stream transmission.

DATA ANALYSIS

Absorption Measurements

Ideally, measurement of absorption at three wavelength bands by the three gases of interest would provide sufficient information to yield the three concentrations required provided that the three species each absorb independently with no overlapping or interferring absorption occurring between the bands. This is not the case in the wavelength region chosen or in any other where absorption occurs within a suitably narrow region of wavelength. Since the basic mechanism of absorption for all three species in the 2.0-2.5 μm region is the same ($C-H_n$ bond interactions), there is a significant amount of overlapping and interferring absorption exhibited. (See Figs. 5, 6 and 7.) However, measurements taken at the four wavelengths chosen provide enough data, when applied in the methods described below, to determine the three concentrations within the level of accuracy required.

Linear (Beer's Law) Theory

Beer's law describes the relation of absorption of light by single or multiple species to the concentration of the species present. For a low concentration of a single gas absorbing monochromatic light, Beer's law states that the relative absorption per unit path length is proportional to the partial pressure (concentration) of the absorbing component. Beer's law may be written as a differential equation of the form:

$$\frac{-1}{y} \frac{dy}{dp} = \alpha x \tag{1}$$

where "y" is the intensity of the transmitted light after absorption, "dp" describes the path length over which absorption takes place, "x" is the partial pressure of the absorbing gas, and "α" is the proportionality constant. When integrated over a finite path length, "P", equation (1) may be expressed as:

$$z = ax$$

$$\text{where } z = \ln (y_0/y) \tag{2}$$

$$\text{and} \quad a = \alpha P.$$

Here, "z" might be called the logarithmic absorption and "y_0" is the intensity of light passing through the absorption path length with no absorbing gas present.

For three species of absorbing gas, Beer's law expands to:

$$z = a_1 x_1 + a_2 x_2 + a_3 x_3$$

$$\text{or } z = \sum_{j=1}^{3} a_j x_j$$

Within the FBDR system, absorption is measured at four wavelengths and equation (3) becomes a system of equations:

$$z_i = \sum_{j=1}^{3} a_{ij} x_j \text{ for } i = 1,2,3,4. \tag{4}$$

In matrix form (4) becomes $Z = AX$

The values of a_{ij} are coefficients describing absorption curves generated during calibration for each gas at each of the four wavelengths through the fixed absorption path length.

The absorption curves are determined by making measurements of absorption at five concentrations of each gas ($\cong$ 1, 2.5, 5, 15 and 30%) at the four wavelengths.

Data analysis for the instrument system works directly with the set of equations in (4). The over-determined system (four equations and three unknowns) may be solved through linear least squares methods, the end result being a matrix equation:

$$X = BZ$$

$$\text{where } B = (A^T A)^{-1} A^T \tag{5}$$

provided the inverse matrix exists.

Non-Linear Results and Iterative Solutions

As described above, calibration procedures yield twelve sets of measurements describing curves (four wavelength channels and three species of gas at various concentrations) to which functional forms were to be fitted. Channel outputs were read from the A/D converter which gives data numbers (DN) in the range of 0-4095. An assumed functional form was taken as providing an adequate fit to the calibration data if r.m.s. deviations between observed and computed, (back-calculated) output levels were less than five DN.

For each instrument, it was found that nearly half of the twelve curves could be fitted with the form in equation (2). With the exception of one, the remaining curves could be fitted adequately to a three parameter form:

$$z = a_1x + a_2x^2 + a_3x^3 \tag{6}$$

which is an elaboration of equation (2).

For methane data at 2.36 μm a better fit was obtained using a form

$$\log(z) = c_0 + c_1q + c_2q^2 \tag{7}$$

$$\text{where } q = \log(x)$$

This form is equivalent to (2) if $c_1 = 1$ and $c_2 = 0$.

Assuming that, in multiple species mixtures of the three gases, inter-species reactions do not occur which change their individual absorption characteristics, the additive logarithmic absorption by each specie present in a multi-gas mixture will superpose. This superposition was in fact demonstrated by analyzing multi-gas mixtures with the instruments in the laboratory and obtaining correct individual concentrations of the three gases present in ratios expected under spill test conditions.

Given superposition, a set of equations similar to those in (4) may be written utilizing the data obtained by measuring individual gas concentrations:

$$z_i = \sum_{j=1}^{3} F_{ij}\ (x_j) \tag{8}$$

for $i = 1,2,3,4$.

Because some of the functions, F_{ij}, are found to be slightly non-linear, this system cannot be solved exactly by the matrix inversion technique described earlier. It can, however, usually be solved using a Newton iteration technique.

The continuous nature of the absorption functions suggest a Taylor's series expansion of $z(=\ell n\ (yo/y))$ about some estimated concentration values x_{jest} $(j = 1,2,3)$. Thus:

$$z_i = \sum_{j=1}^{3} \left[F_{ij}\ (x_{jest}) + \left.\frac{dF_{ij}}{dxj}\right|_{x_j=x_{jest}} (x_j - x_{jest}) + \ldots \right] \tag{9}$$

for $i = 1,2,3,4$.

Neglecting higher terms and rearranging remaining terms gives

$$(dz_i) = \sum_{j=1}^{3} a_{ij}\ (dx_j) \qquad \text{for } i=1,2,3,4. \tag{10}$$

where $dz_i = z_i - \sum_{j=i}^{3} F_{ij}\ (x_{jest})$,

$$a_{ij} = \left.\frac{dF_{ij}}{dx_j}\right|_{x_j = x_{est}},$$

and $dx_j = x_j - x_{jest}$

In matrix form equation (10) becomes

$$(dz) = A(dx) \tag{11}$$

where A is a 4 x 3 matrix. This equation is similar to equation (4). Using a least squares process similar to that used in deriving equation (5) gives

$$(dx) = B(dz) \tag{12}$$

where $B = (A^T A)^{-1} A^T$ provided the inverse exists. The revised concentration estimate is thus

$$\begin{aligned} X &= X_{est} + (dx) \\ &= X_{est} + B(dz) \end{aligned} \tag{13}$$

This expansion, linearization, and revision process can be applied iteratively until successive applications produce no palable changes in concentration estimates x_j for $j=1,2,3$.

Because a linear relationship (Beer's law) is at least approximately followed by the FBDR data, the effect of neglecting higher order terms in the expansions is generally not significant. Accordingly the convergence in the iterative solution method is fairly rapid and this method has provided concentration results for multi-gas test mixtures within the accuracy required of the FBDR systems.

INSTRUMENT APPLICATION

Future use of the FBDR instruments for 40 cubic meter and larger volume tests will yield data to permit accurate models of LNG despersion to be generated. When applied in the general case these data will enable safe location of transfer terminals and better regulation of transport of LNG as it becomes more and more widely depended upon as an energy source in this country.

APPENDIX 1

Spill Test Results

During the summer of 1980 the FBDR prototype was deployed in an instrument array at the Naval Weapons Center, China Lake, California, for three 40 cubic meter LNG spill tests.

These were designated LNG-32, LNG-33 and LNG-34. Figure 9 shows the instrumentation array at China Lake. The array center line is orientated with the direction of the prevailing winds (225° true). Instrument station masts are positioned at several radii from the spill point with instruments mounted at 1, 3 and 8 meter heights. Several types of stations are included in the array. The Gas Sensor Stations employ commercial hydrocarbon sensors to give averaged total hydrocarbon concentration data. The anemometer stations carry bi-vane anemometers to give wind field data. The Turbulence Stations carry fast response gas sensors which are capable of differentiating the LNG hydrocarbon species and fast response three axis anemometers. This combination of instrumentation gives detailed turbulence and concentration data to describe the dispersing LNG. For the first two tests (LNG-32 and LNG-33), the instrument was placed at 1 meter height on Turbulence Station 5 (T-5) (400 meters down range from the spill point) and on Turbulence Station 4 (T-4) (140 meters down range) at 1 meter for LNG-34. Figure 10 is a photograph of the FBDR as it was deployed with other instruments on the station mast.

LNG-32

The test was conducted August 27, 1980, at 6:12 p.m. Winds were from 208° true at 8.4 meters/sec. Because the winds were too much from the south, the cloud traveled west of center line and i ssed the Instrument location and hence no LNG vapors were detected by the FBDR. The test did verify that data were being output from the instrument and being received by the FDAS under actual spill conditions.

LNG-33

The test was conducted on September 3, 1980, at 7:09 p.m. Winds were from 234.8° true at 1.8 meters/sec. Approximately 800 seconds of data were obtained from the instrument during this test with peak levels of methane, ethane and propane, detected at 2.6,0.15, and 0.05% respectively, at the instrument position 400 meters down range.

LNG-34

This test was conducted on September 17, 1980, at 6:37 p.m. Winds were from 232.3° true at 5.7 meters/sec. The instrument, positioned 140 meters down range, detected levels of methane, ethane and propane over a 150 second period, of 5.0, 3.0, and 0.4% respectively.

Comparison of LNG-33 and LNG-34

Figure 11 shows the LNG cloud approximately 300 seconds into the LNG-33 test. Figure 12 shows the cloud during LNG-34 approximately 50 seconds into the test. As noted above, the wind speeds for these two tests were quite different. Under the higher wind speeds during LNG-34 the cloud obviously traveled down range much faster than in LNG-33 but also was much more broken up by the winds. The differing character of the spill dispersion caused a basic difference in the appearance of the data in these two tests. During LNG-33 the instrument saw one cloud for an extended period of time and indicated concentrations increasing to a peak and then trailing off. The LNG-34 data showed two separate clouds passing the instrument location, the second delayed by approximately 70 seconds and showed methane, ethane and propane concentration of 3.0, 0.2 and 0.4% respectively. It should also be noted that at 400 meters down range during LNG-34, several broken clouds of LNG were detected whereas during LNG-33 the single cloud seemed to remain intact as it passed throughout the entire array.

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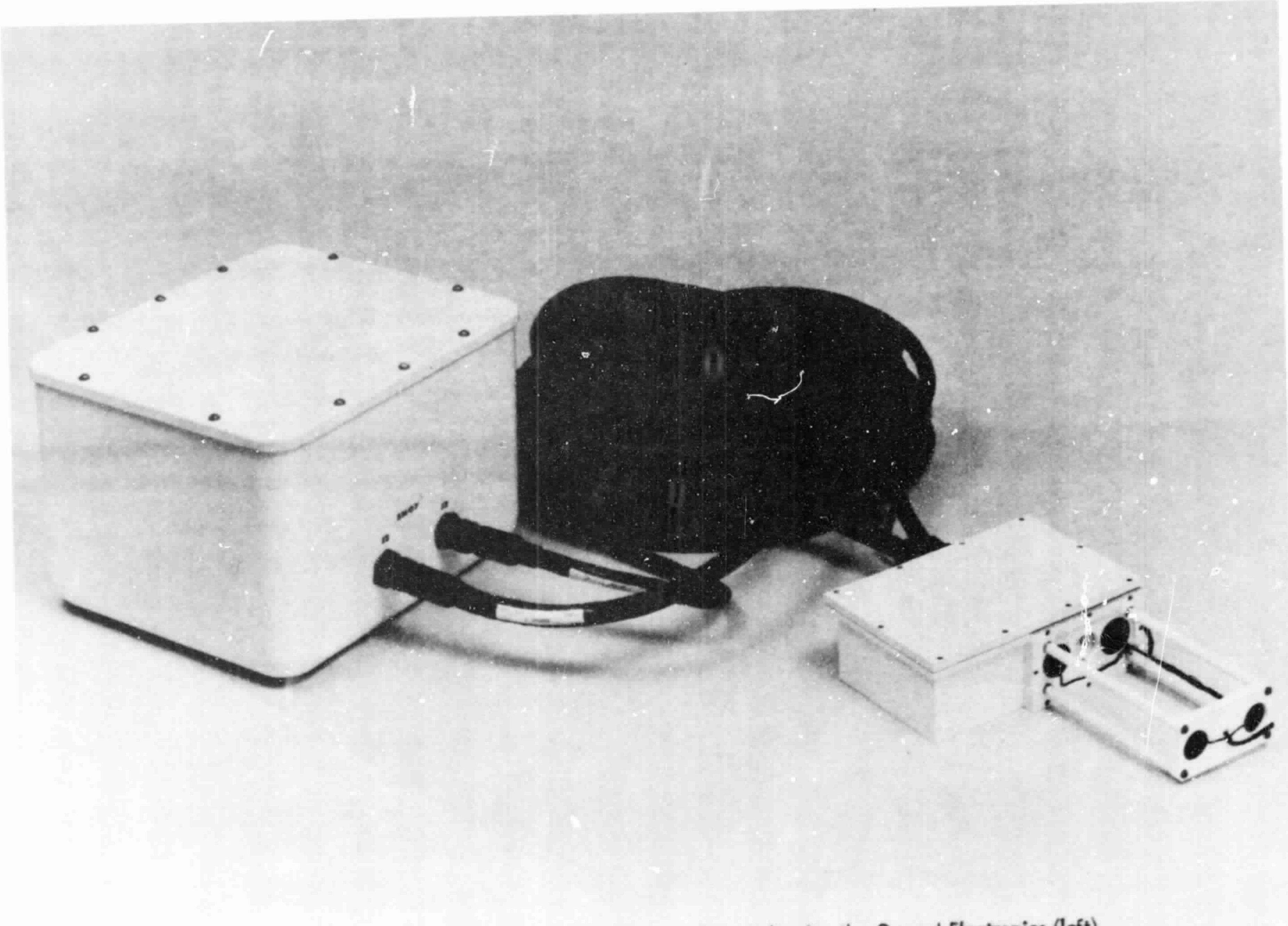

Figure I. Photograph of the FBDR Instrument System showing the Ground Electronics (left), cabling, and Sensor Head (right).

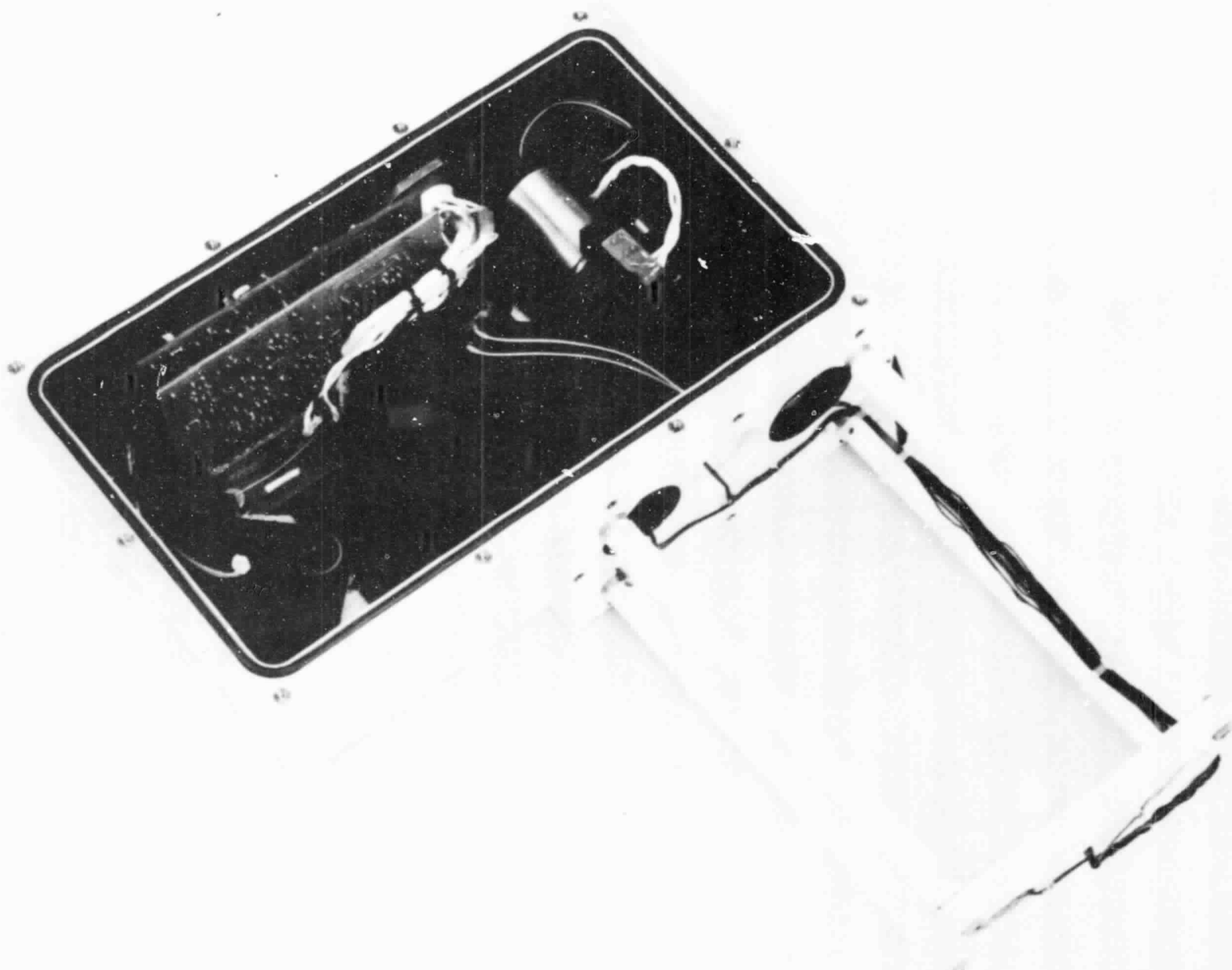

Figure 2. Photograph showing the interior of the FBDR Sensor Head.

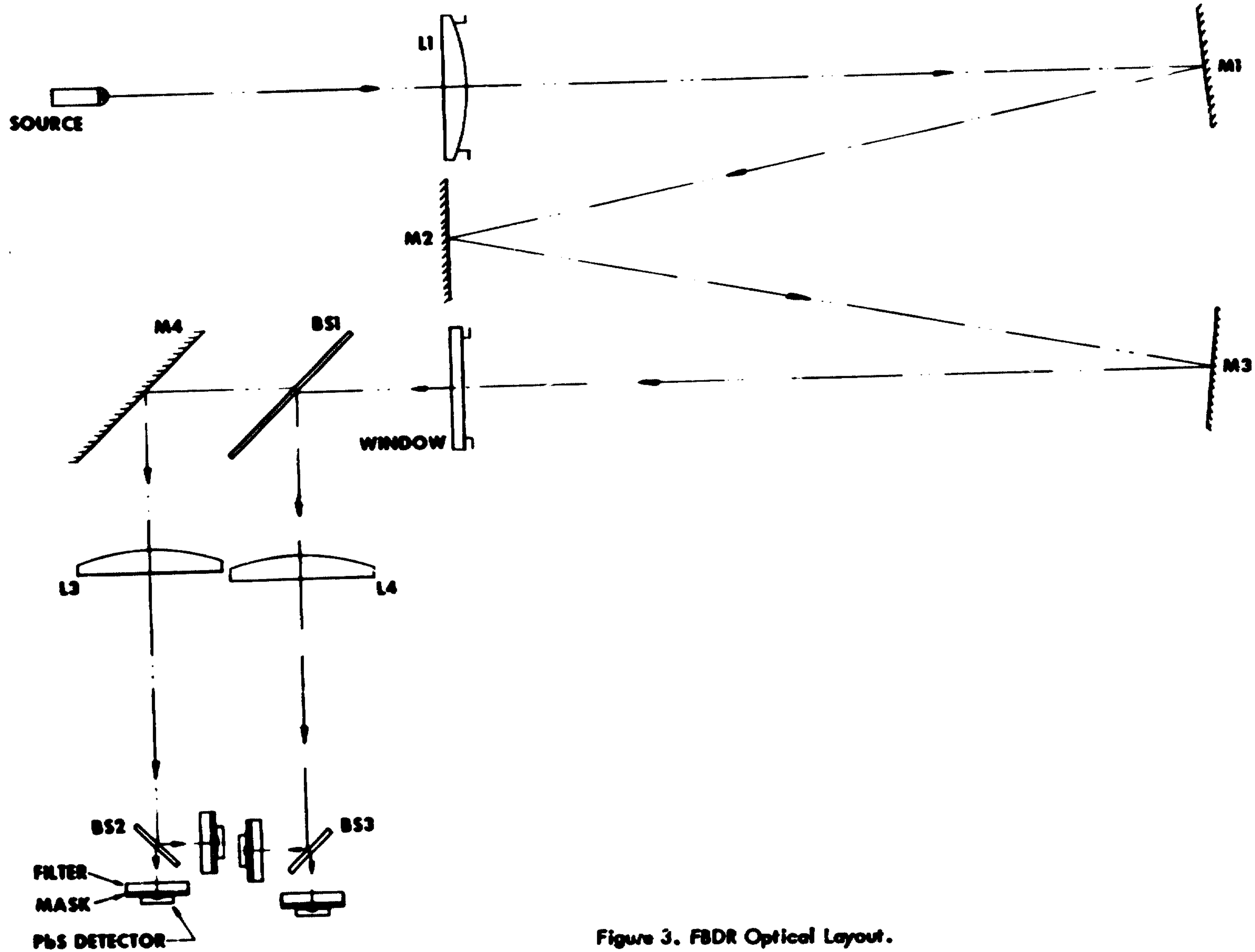

Figure 3. FBDR Optical Layout.

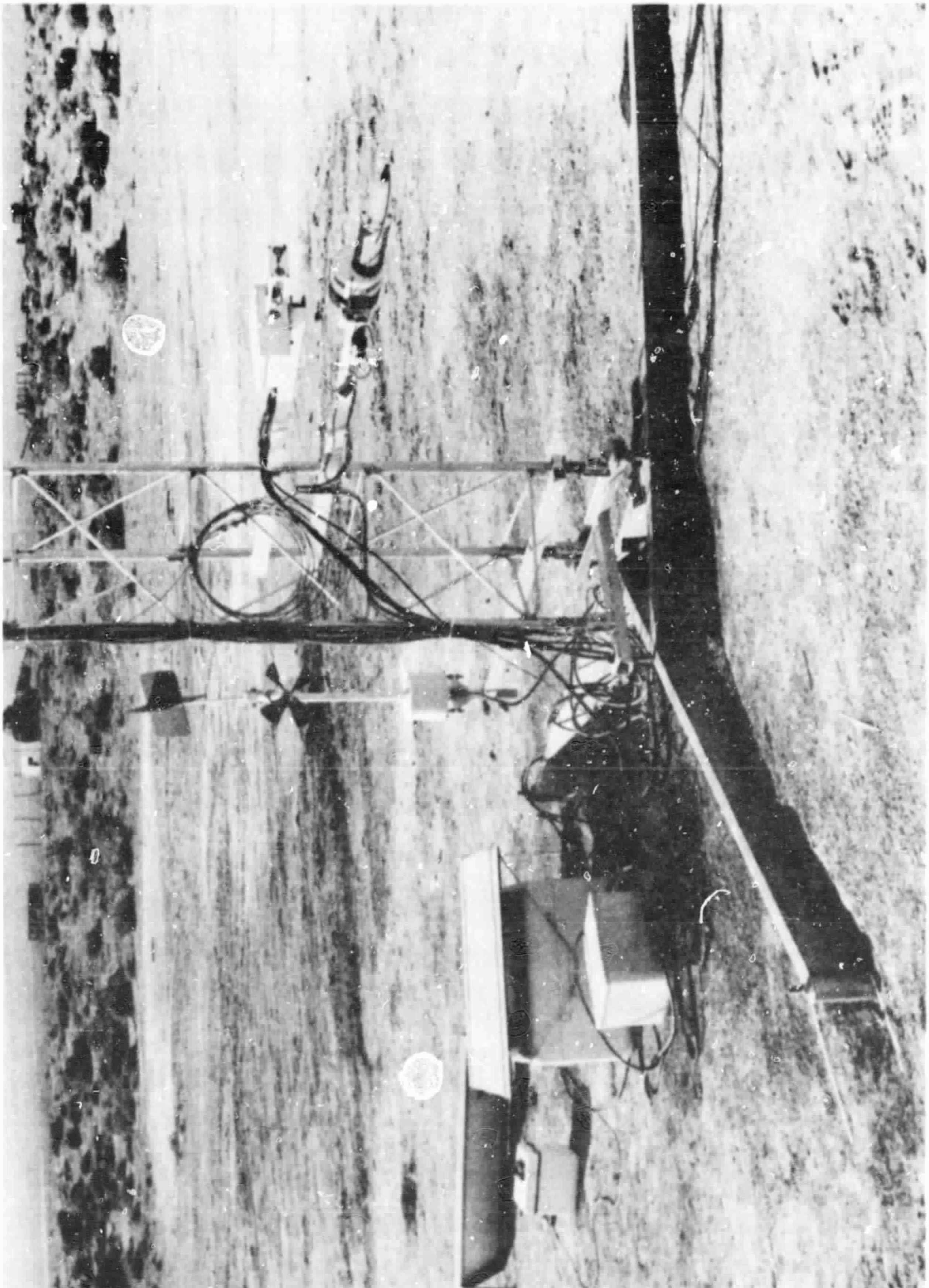

Figure 4 . FBDR system as deployed for LNG spill tests.

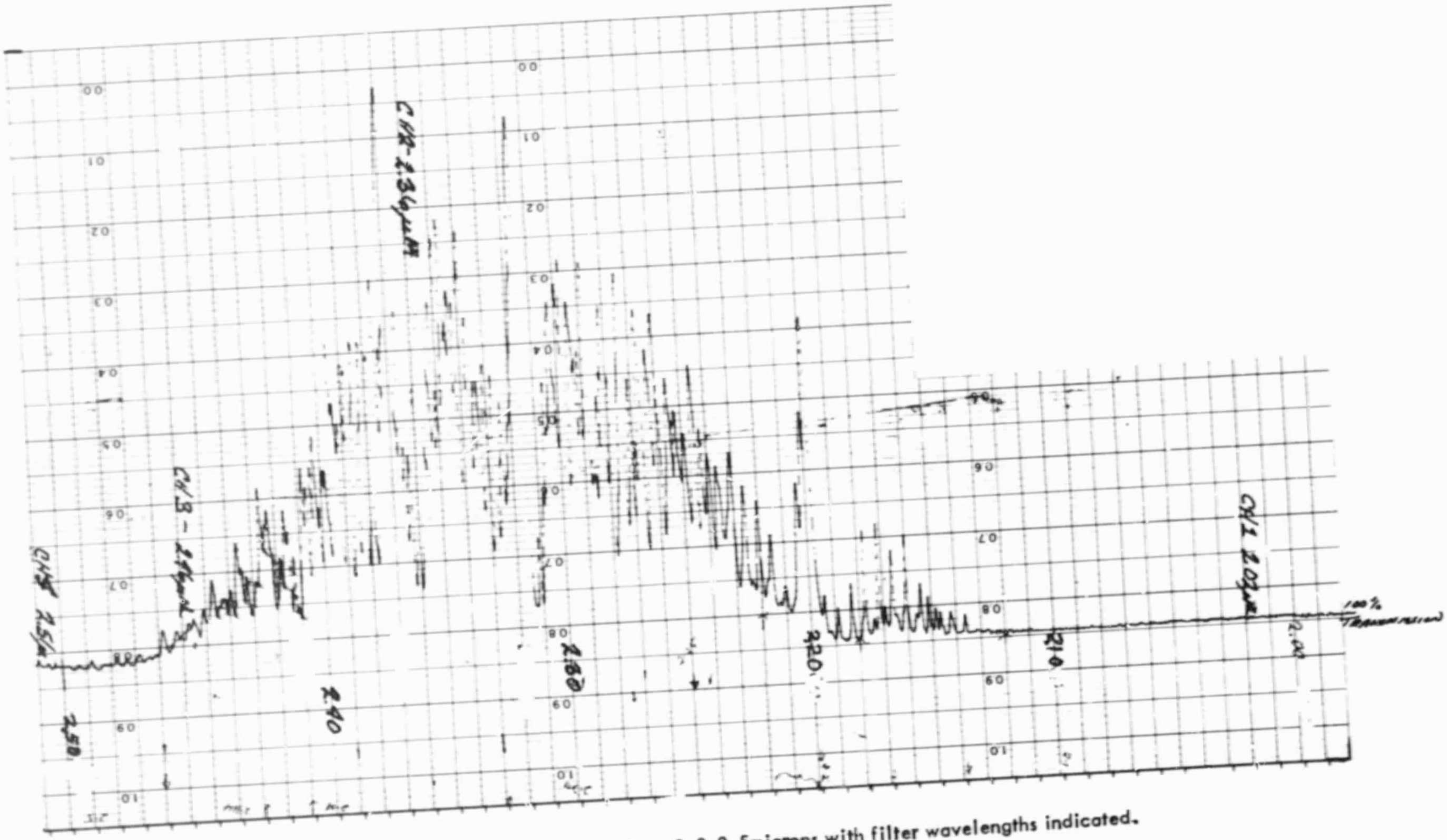

Figure 5. Methane transmission specira from 2.0–2.5microns with filter wavelengths indicated.

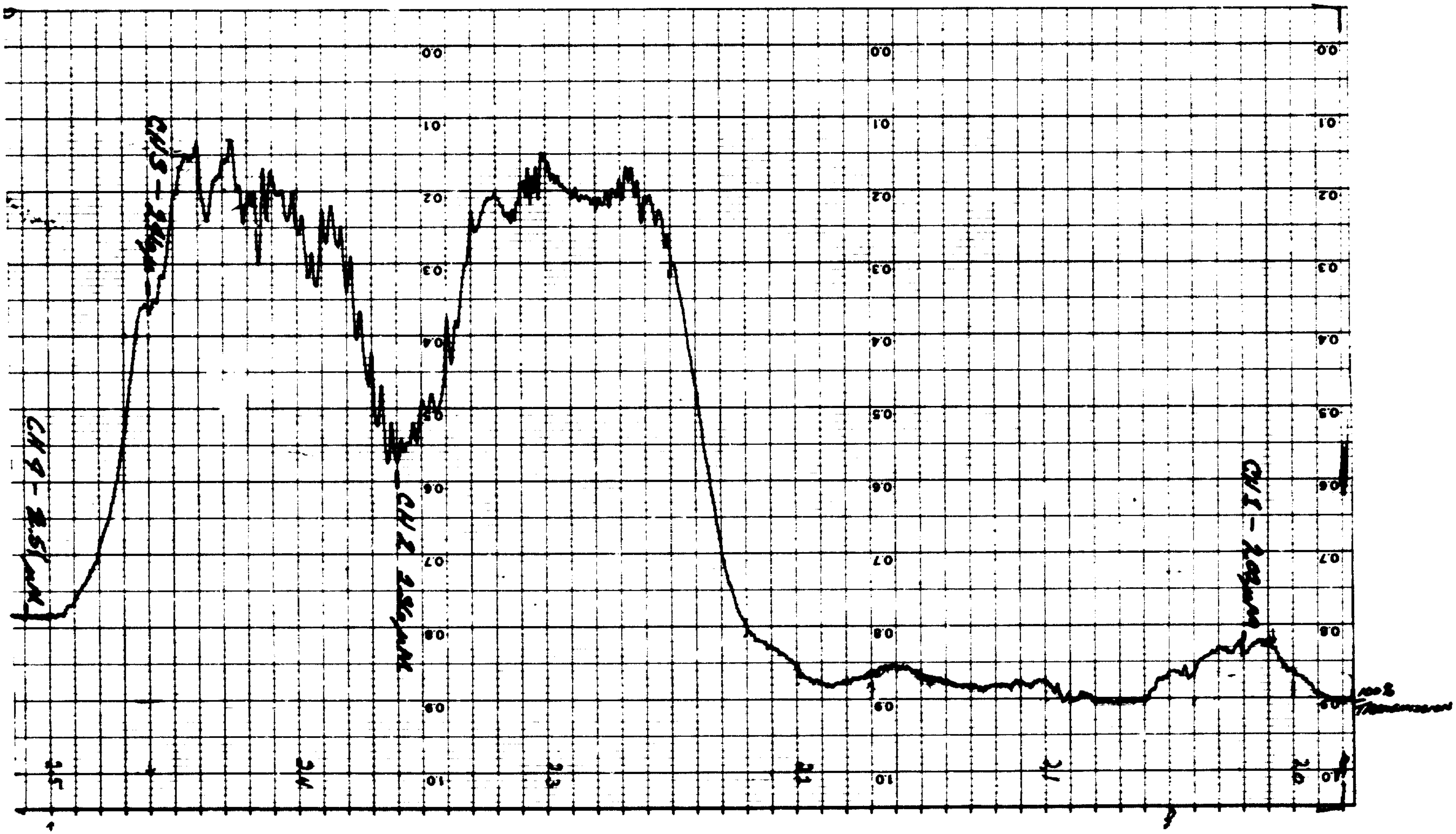

Figure 6. Ethane transmission spectra from 2.0–2.5 microns with filter wavelengths indicated.

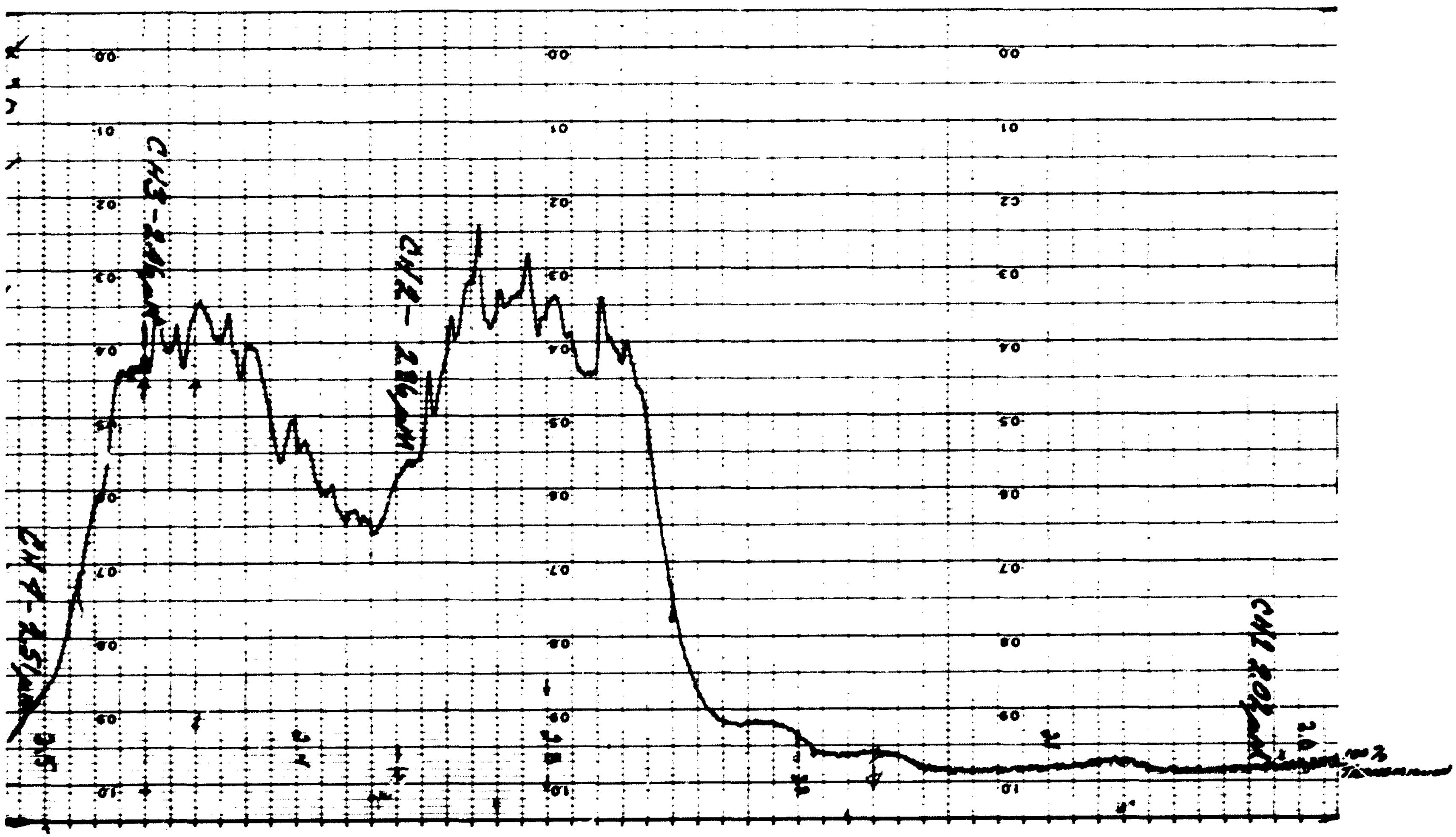

Figure 7. Propane Transmission spectra from 2.0–2.5 microns with filter wavelengths indicated.

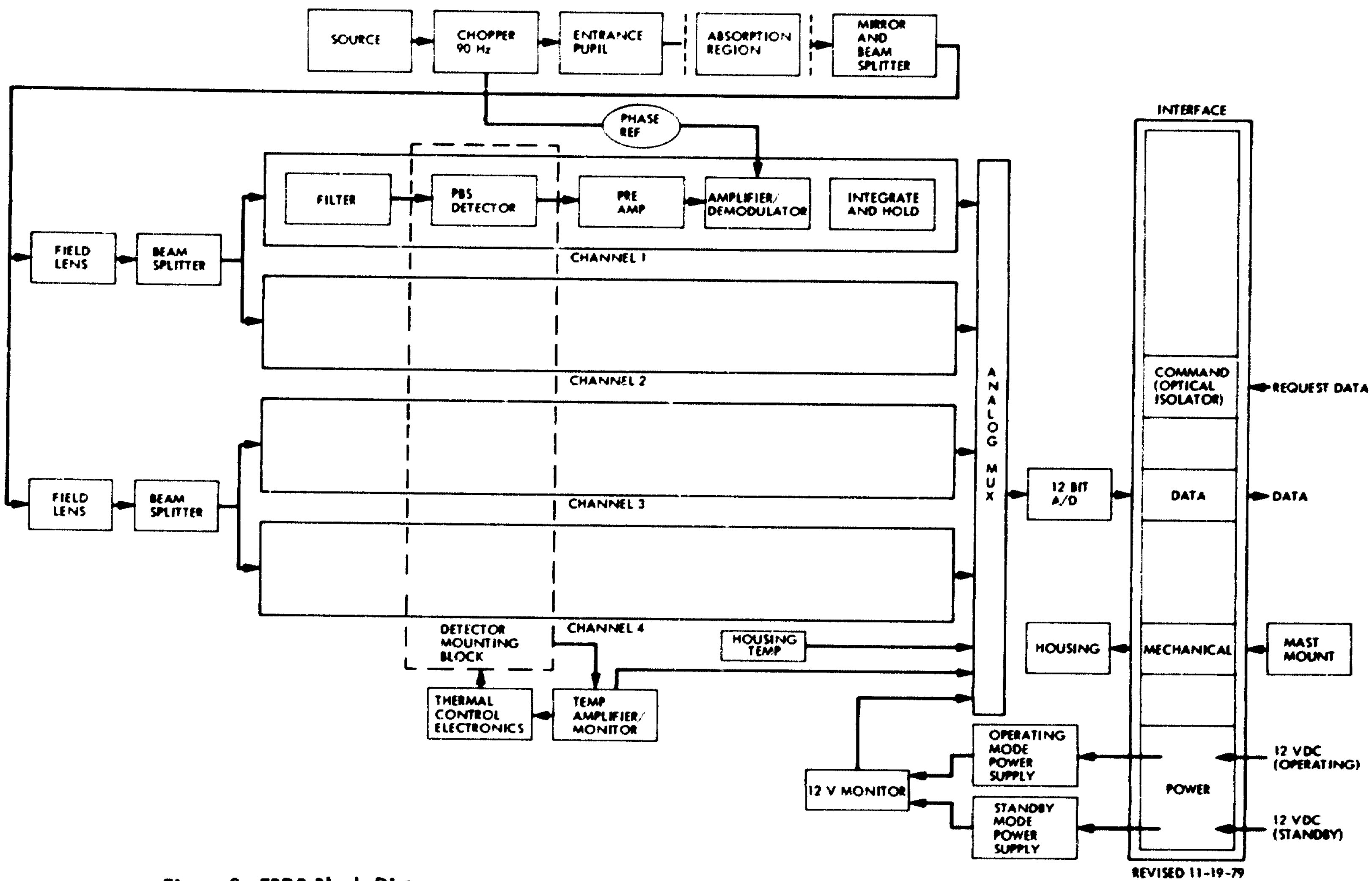

Figure 8. FBDR Block Diagram.

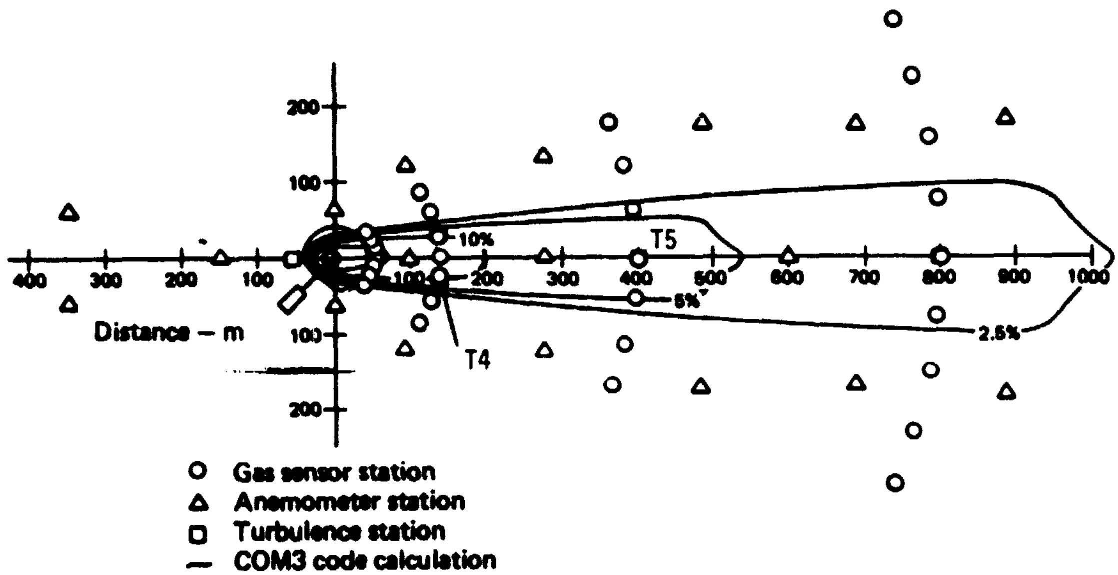

Fig.9. Far field dispersion array for 40-m^3 spill tests at China Lake.

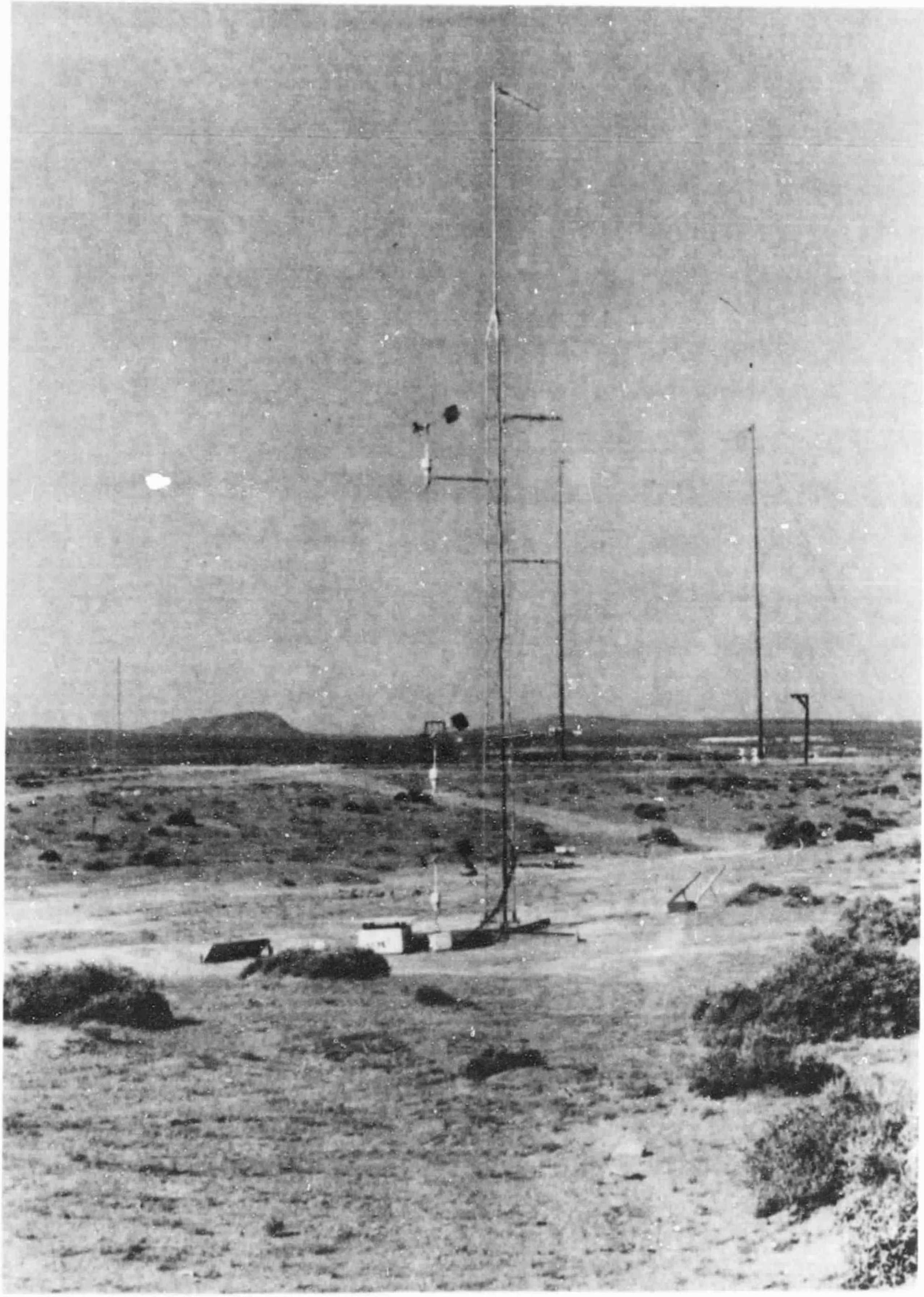

Figure 10. FBDR mounted on Turbulence Station mast with other instrumentation.

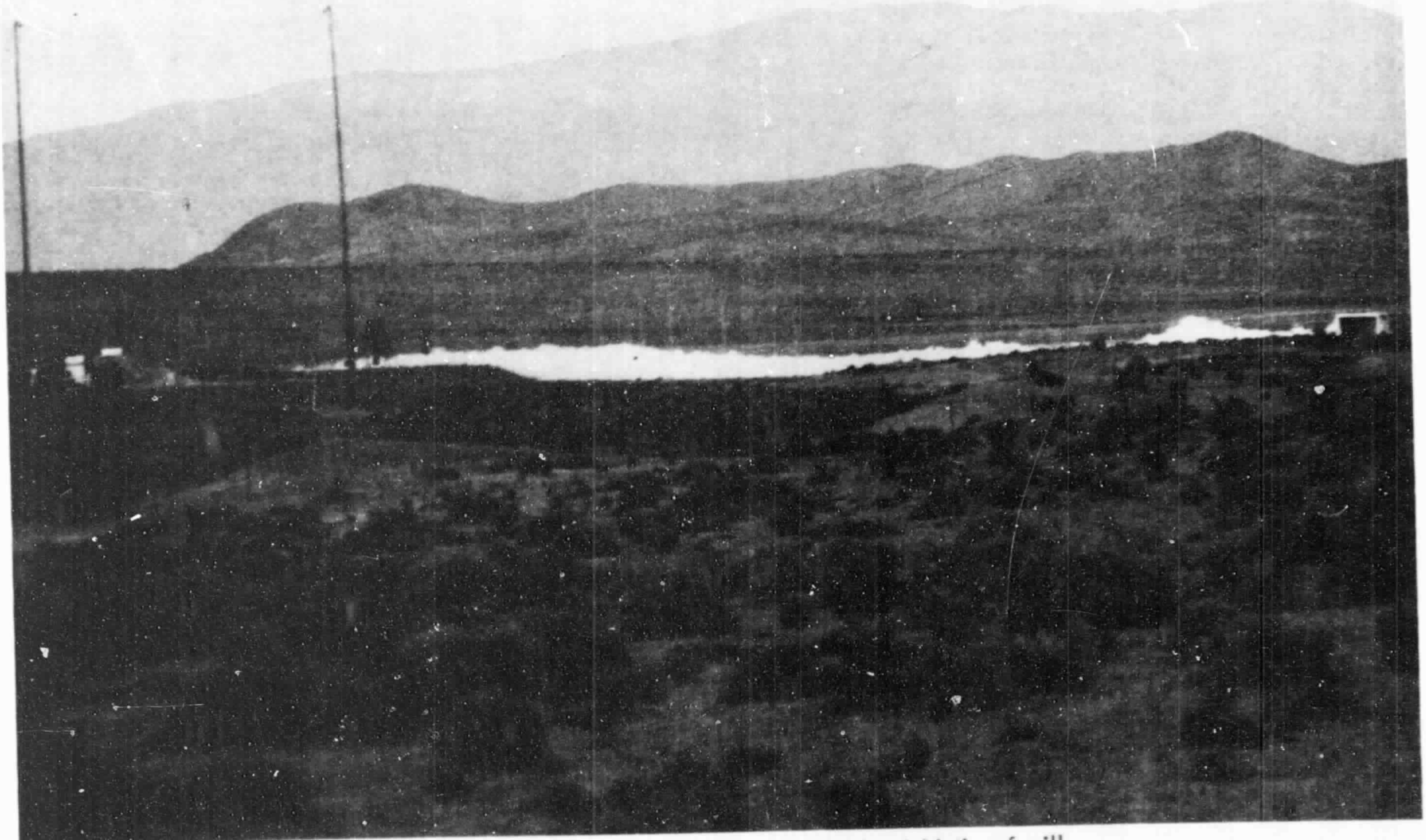

Figure 11. LNG 33 approximately 300 seconds after initiation of spill.

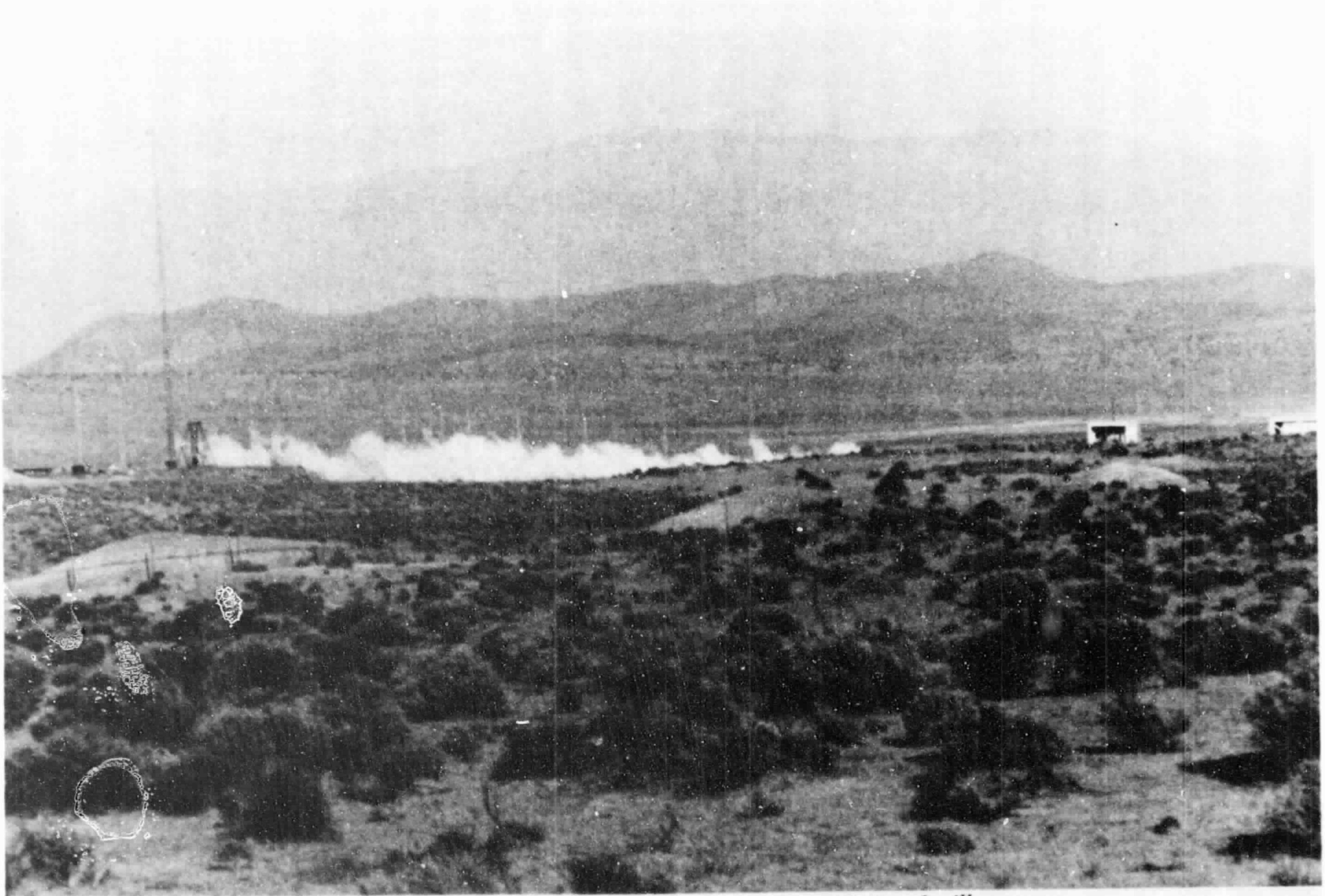

Figure 12. LNG 34 approximately 50 seconds after initiation of spill.